Proton structure at high Q^2

Kunihiro Nagano (KEK/DESY)

on behalf of

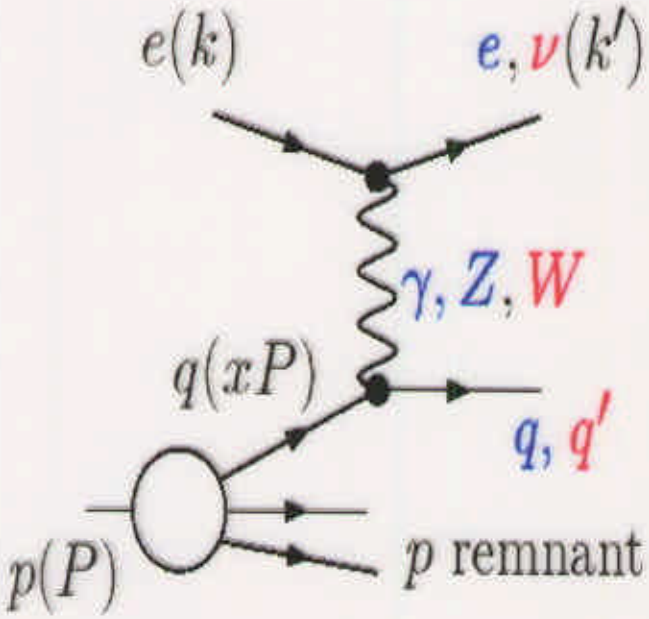
the H1 and ZEUS collaborations

30th International Conference on High Energy Physics
(ICHEP 2000)

July 27 – August 2, 2000 in Osaka, Japan.

Deep Inelastic Scattering (DIS)

DIS is a straightforward tool to probe p structure.



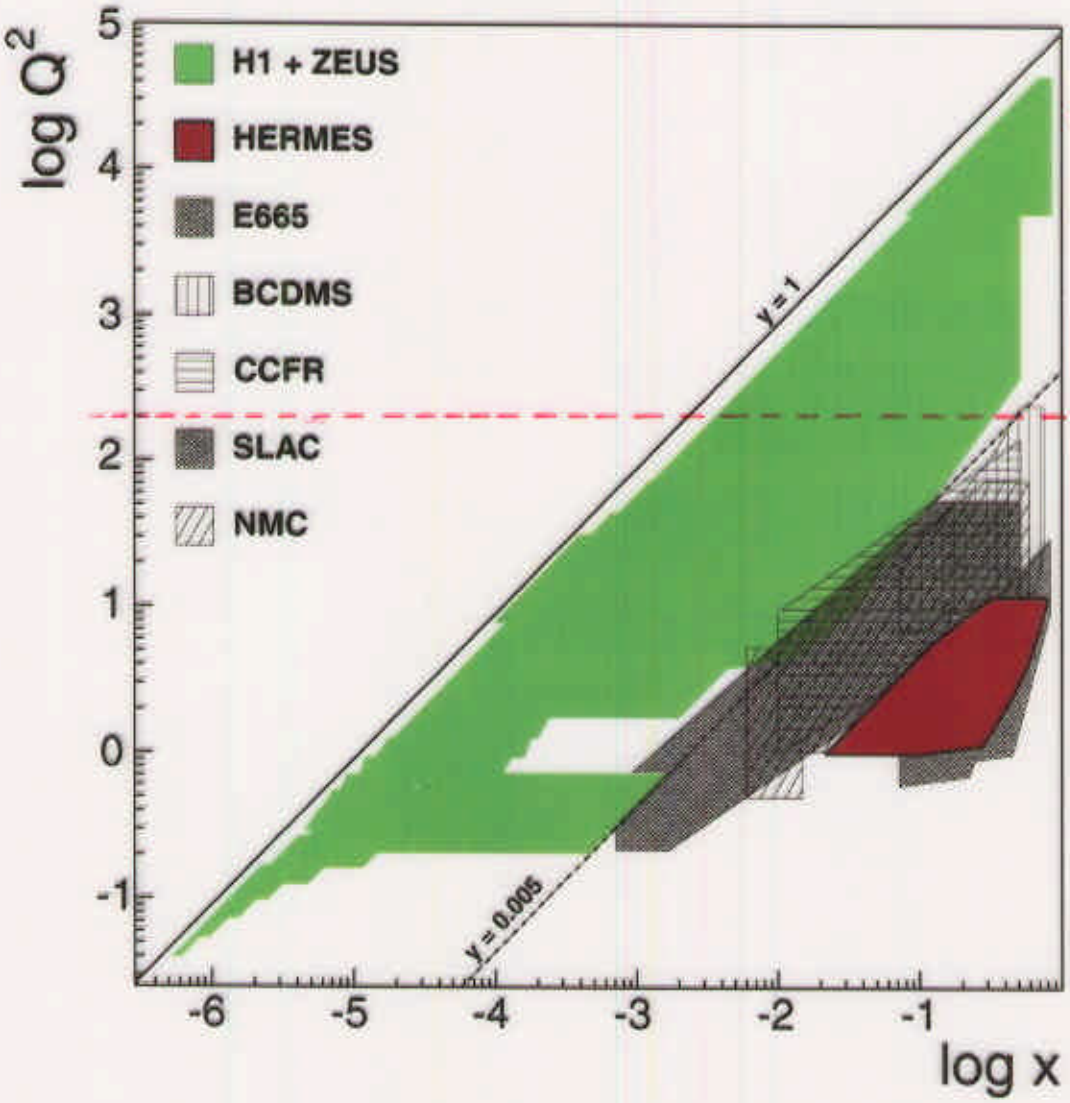
- $Q^2 \equiv -(k-k')^2 \equiv -q^2$
- Bjorken scaling variable (=momentum fraction)
  $$x \equiv Q^2/2p \cdot q$$
- inelasticity of electron (reflects scattering angle of e in eq CMS, θ^*)
  $$y \equiv p \cdot q/p \cdot k = \frac{1-\cos\theta^*}{2}.$$
- $Q^2 = x \cdot y \cdot s$

Inclusive DIS cross-sections $\Leftrightarrow$ Structure functions (SFs)

Parton densities and DGLAP evolution

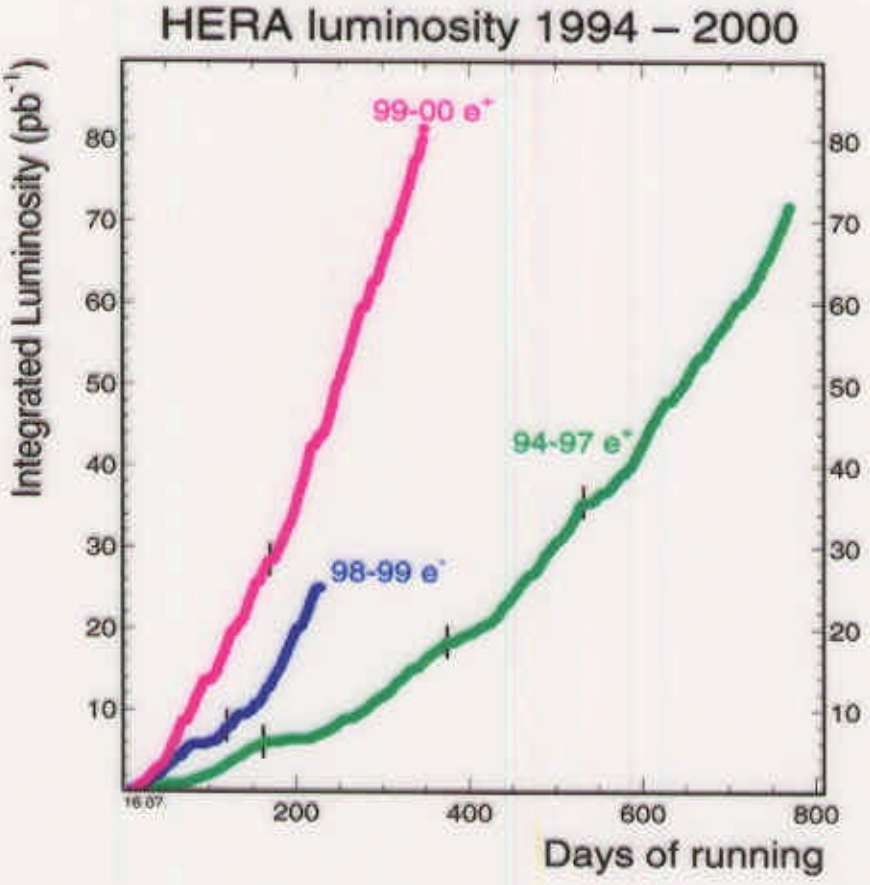
- SFs = sum of (short-range) $\otimes$ (parton density).
- Parton density includes long-range effects. In spite, pQCD can predict "evolution" of PDFs in Q^2; DGLAP equation.
- Needs experimental inputs to determine initial parton densities at Q_0^2 where evolution starts.

DIS at HERA, the first ep-collider



- Medium Q^2: precise measurement of SFs.
  - determination of sea-quark and gluon densities at low-x.
  - high y : F_L.
  - low y : overlap to fixed-target.
- High Q^2: pQCD holds? search for QCD breakdown.
  - Smallest spatial-resolution: $\lambda \sim 1/\sqrt{Q^2}$.
    $Q^2_{\mathrm{max}} \sim 1 \times 10^5$ GeV^2 $\Rightarrow \lambda < 10^{-16}$ cm.
  - NC and CC can be seen at the same place!

HERA luminosity



- '94–'97 : 27.5 GeV e^+ with 820 GeV p.
  H1(ZEUS) : 36.6(47.7) pb^{-1}. ⇒ Published.
- '98–'99 (Apr.): 27.5 GeV e^- with 920 GeV p.
  H1(ZEUS) : 15.3(16) pb^{-1}. ⇒ New preliminary!
- '99(Jul.)–'00: 27.5 GeV e^+. with 920 GeV p.
  H1 : 45.9 pb^{-1} analyzed. ⇒ New preliminary!

Contents of this talk

High-Q^2 DIS ($Q^2 \gtrsim 200$ GeV^2).

We have all; e^+, e^-, NC, CC, at the same apparatus, HERA!

DIS cross-section formula

NC($e^{\pm}p \to e^{\pm}X$)

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \times \{Y_+ F_2^{NC} \mp Y_- x F_3^{NC} - y^2 F_L^{NC}\}$$

$$(Y_\pm = 1 \pm (1-y)^2)$$

- Structure functions, F_2^{NC}, F_3^{NC}, include quark structure of proton and quark coupling to gauge bosons as well M_Z.

$$\begin{pmatrix} F_2^{NC} \\ xF_3^{NC} \end{pmatrix} = \sum_f \begin{pmatrix} xA_f(q_f + \overline{q_f}) \\ xB_f(q_f - \overline{q_f}) \end{pmatrix}$$

- F_3 is a parity violating term. Sign changes in e^+/e^-.
- F_L is non-zero at NLO-QCD and is only relevant at high y in high Q^2 region.($\sim$ 10%)

CC($e^{\pm}p \to \nu X$) in LO QCD

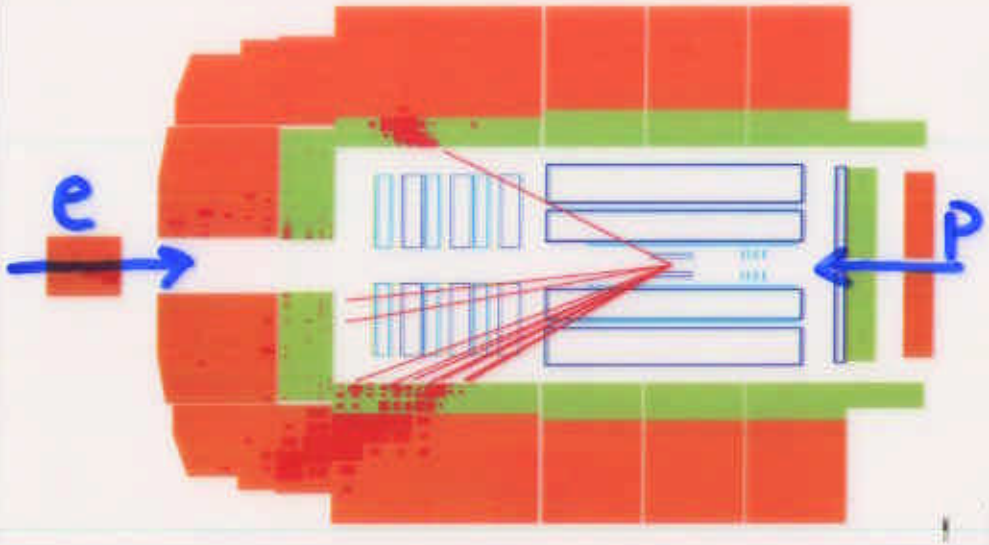
$$e^+p : \frac{d^2\sigma}{dxdQ^2} = \frac{{G_F}^2}{2\pi}\left(\frac{{M_W}^2}{{M_W}^2+Q^2}\right)^2 \times \sum_{i=1,2}[\overline{u_i} + (1-y)^2 d_i]$$

$$e^-p : \frac{d^2\sigma}{dxdQ^2} = \frac{{G_F}^2}{2\pi}\left(\frac{{M_W}^2}{{M_W}^2+Q^2}\right)^2 \times \sum_{i=1,2}[u_i + (1-y)^2 \overline{d_i}]$$

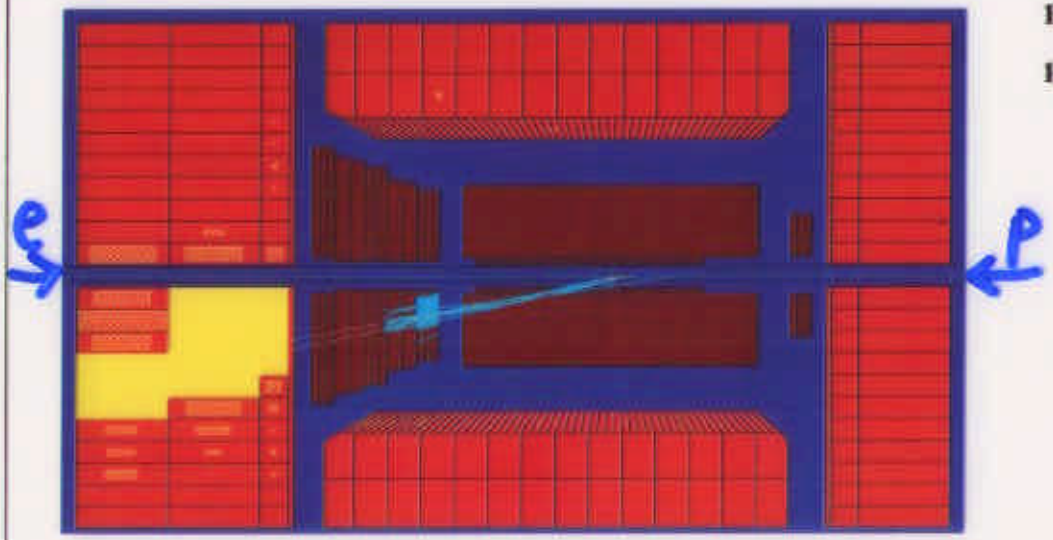
- Flavor selecting; $d(u)$-quark contributes only to $e^+p(e^-p)$.
- Helicity suppression factor, $(1-y)^2$, is multiplied to quarks (antiquarks) in $e^+p(e^-p)$.

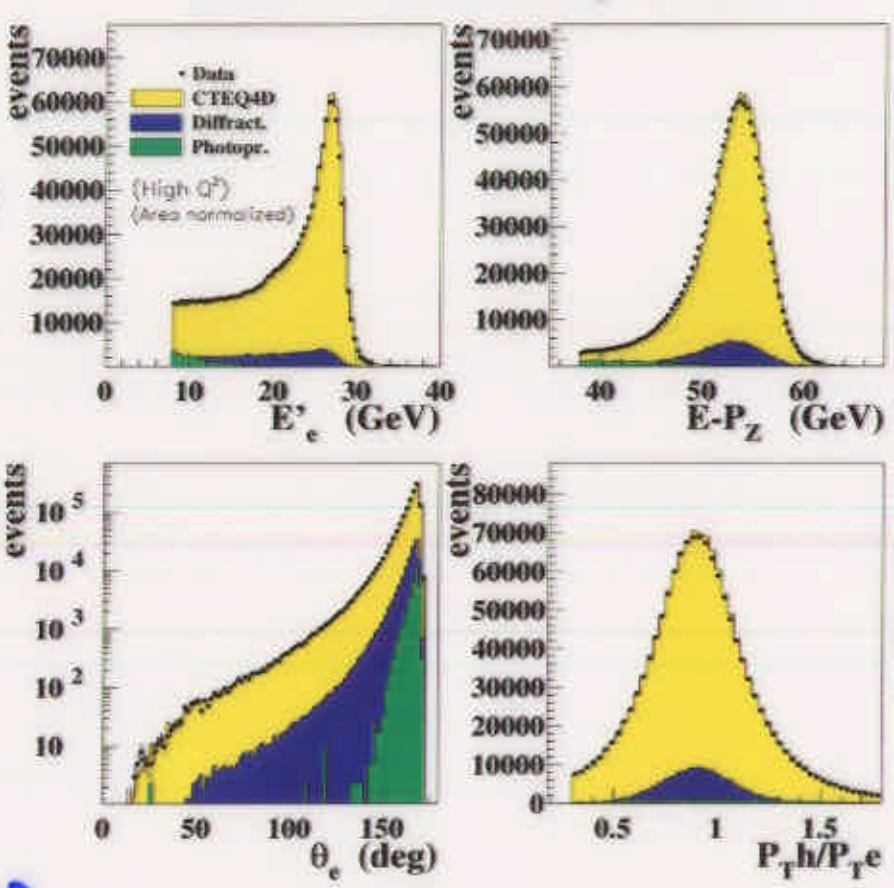
DIS cross-section measurement

NC signature: a large E_T scattered-e.



CC signature: a large $\not{P}_T$ (due to escaped-ν).



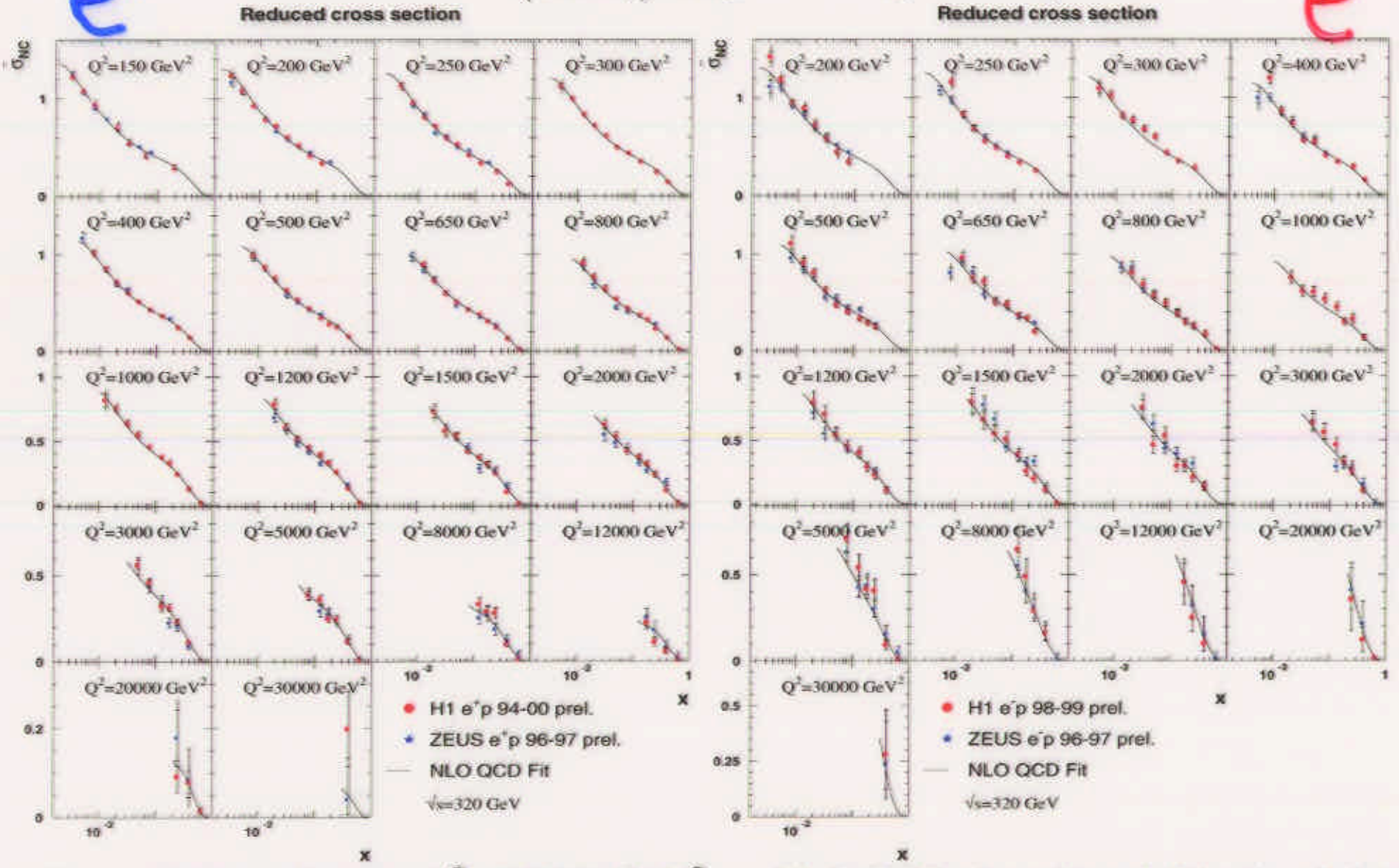


- NC: Both E'_e and θ_e are well reproduced.
- CC: Hadronic energy measurement is crucial. Well understood and checked with $p_T h / p_T e$ in NC data.

NC reduced $\tilde{\sigma}_{NC}$: test of pQCD

$$\tilde{\sigma}_{NC}(e^{\pm}p) \equiv \left(\frac{Q^2 x}{2\pi\alpha^2 Y_+}\right)\frac{d^2\sigma}{dxdQ^2} = F_2^{NC} \mp \frac{Y_-}{Y_+} xF_3^{NC} - \frac{y^2}{Y_+}F_L^{NC}$$

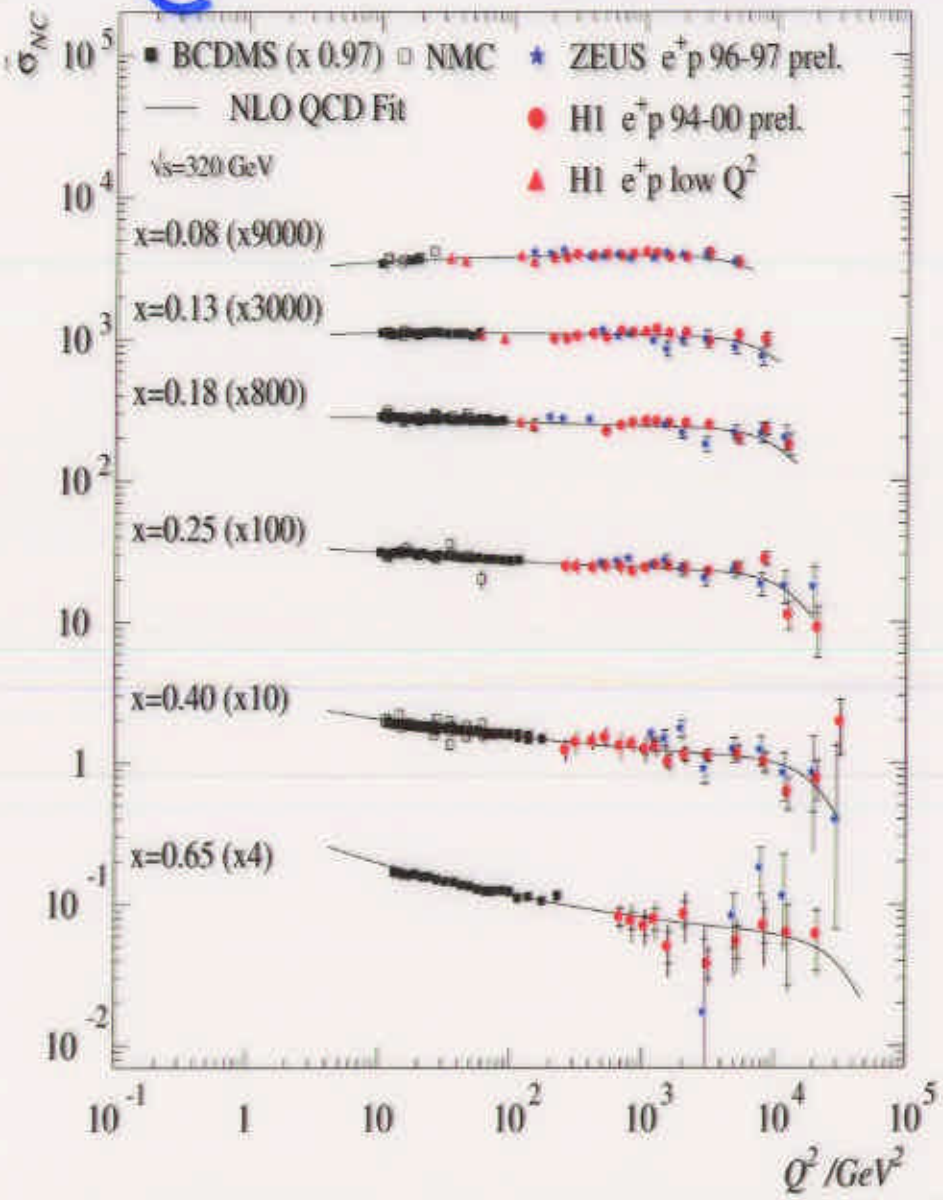
e^+ e^-



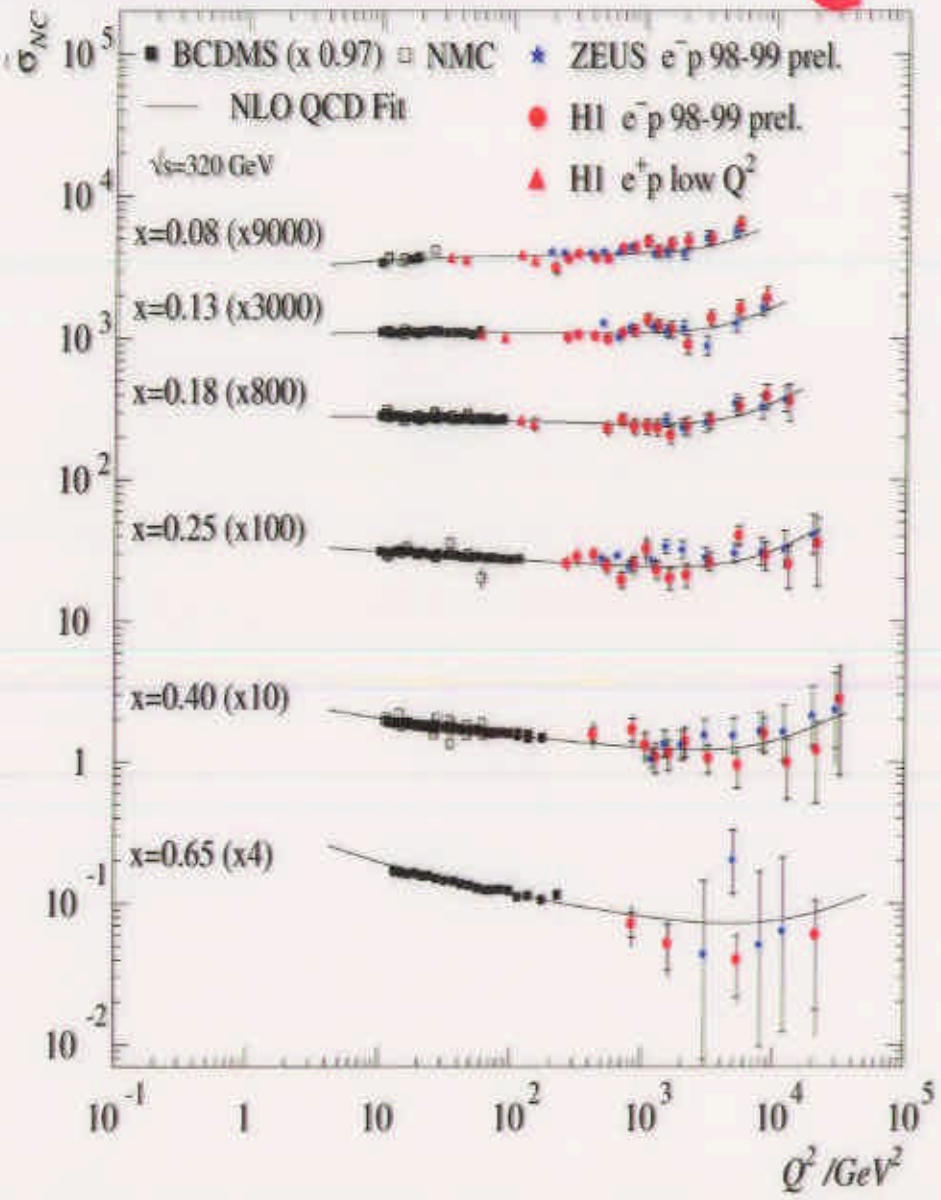
- $\tilde{\sigma}_{NC}$ measured up to Q^2=30000 GeV^2 ⇒ NLO-QCD describes full body of data!

NC reduced $\tilde{\sigma}_{NC}$ at large x, Q^2

e^+



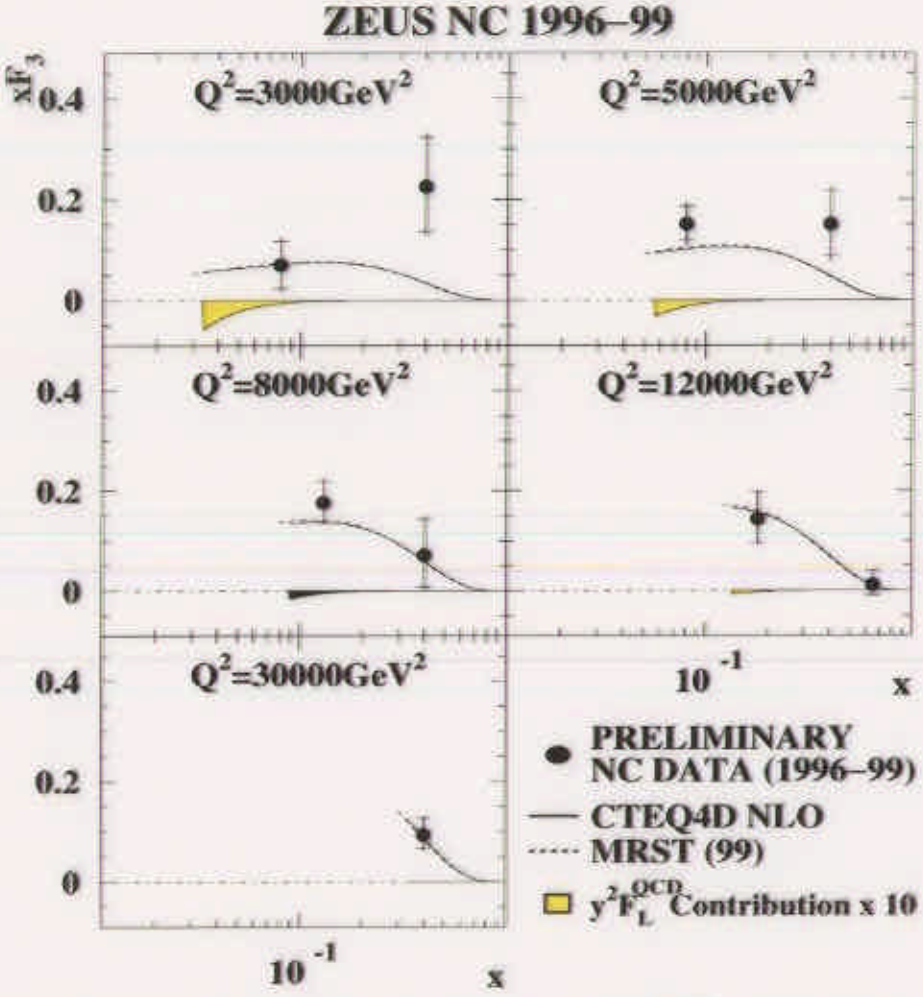
e^-



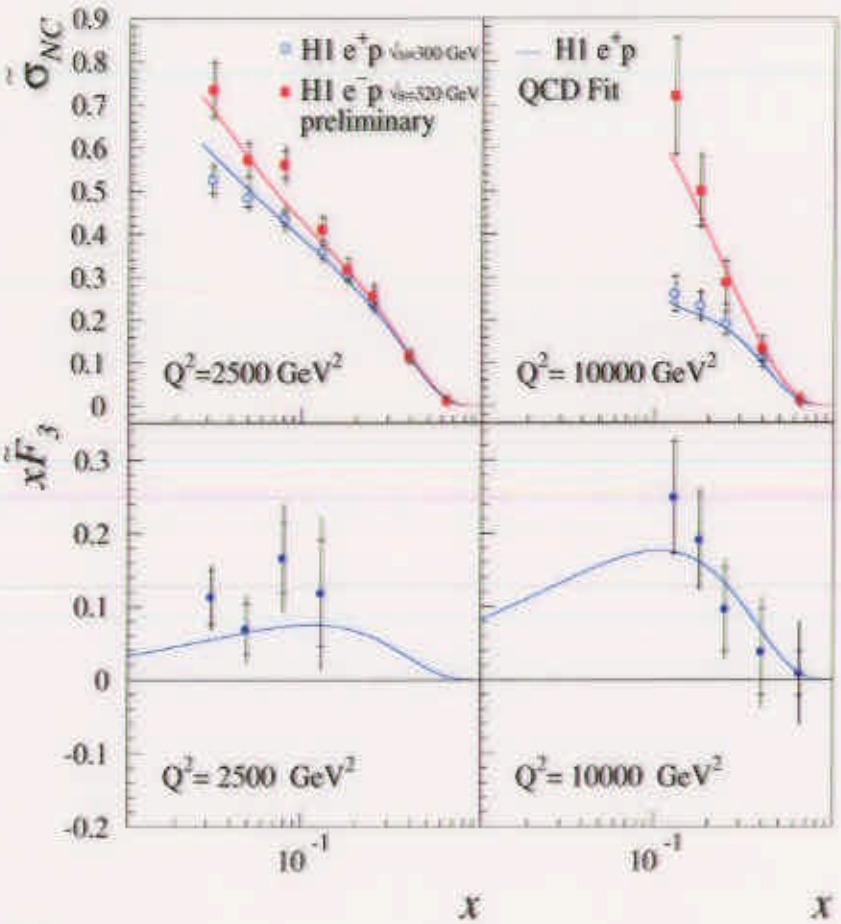
- An excess at x=0.4 observed in H1 e^+p '94–'97 diminished by adding new '99–'00.
- Positive(negative) interference between γ-Z was observed at high-Q^2 in e^- (e^+).

Extraction of xF_3^{NC}

$$\tilde{\sigma}_{NC}(e^{\pm}p) = F_2^{NC} \mp \frac{Y_-}{Y_+} xF_3^{NC} - \frac{y^2}{Y_+} F_L^{NC} \Rightarrow xF_3 = \left(\frac{Y_-^{920}}{Y_+^{920}} + \frac{Y_-^{820}}{Y_+^{820}}\right)^{-1} \{\tilde{\sigma}_{NC}(e^-p) - \tilde{\sigma}_{NC}(e^+p)\} + \Delta F_L$$



(Different beam energy = different y for same (x,Q^2).)

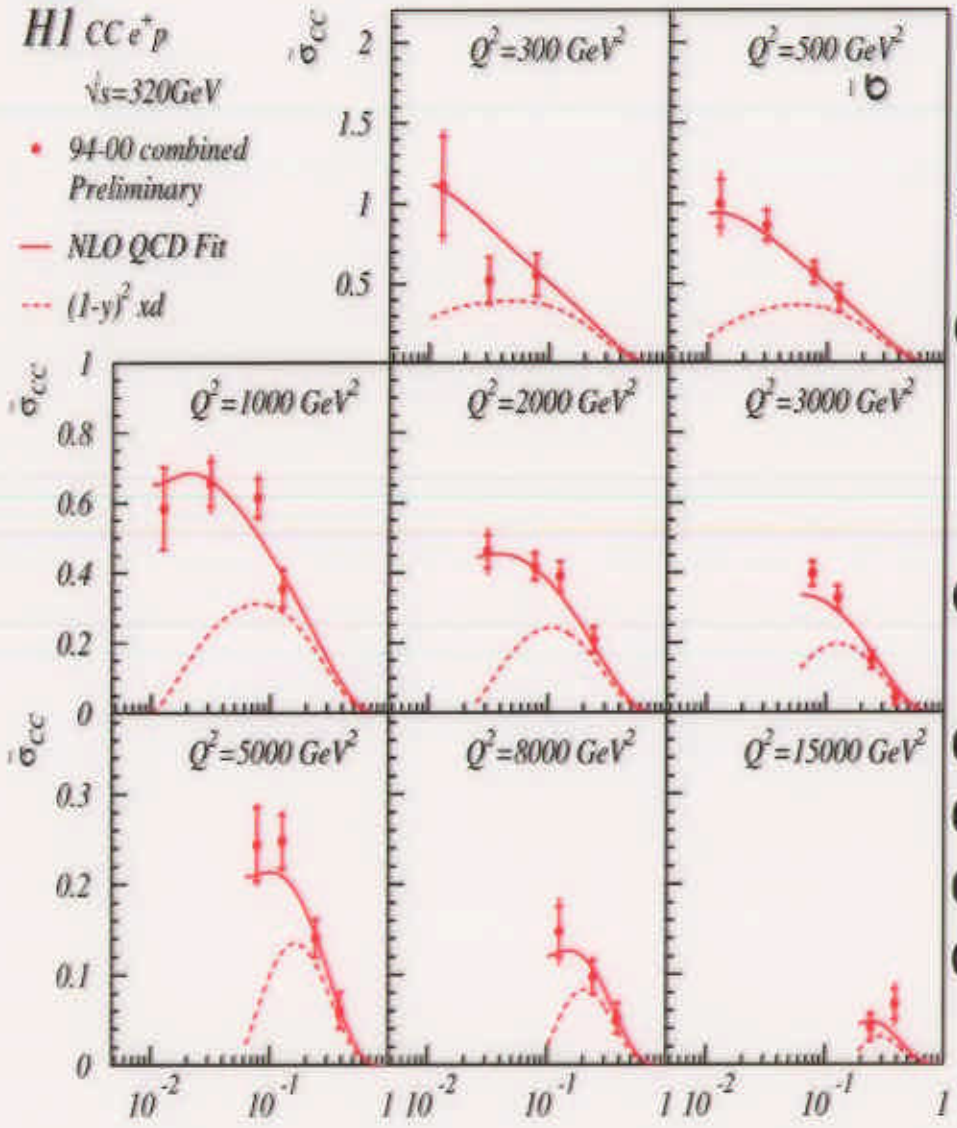


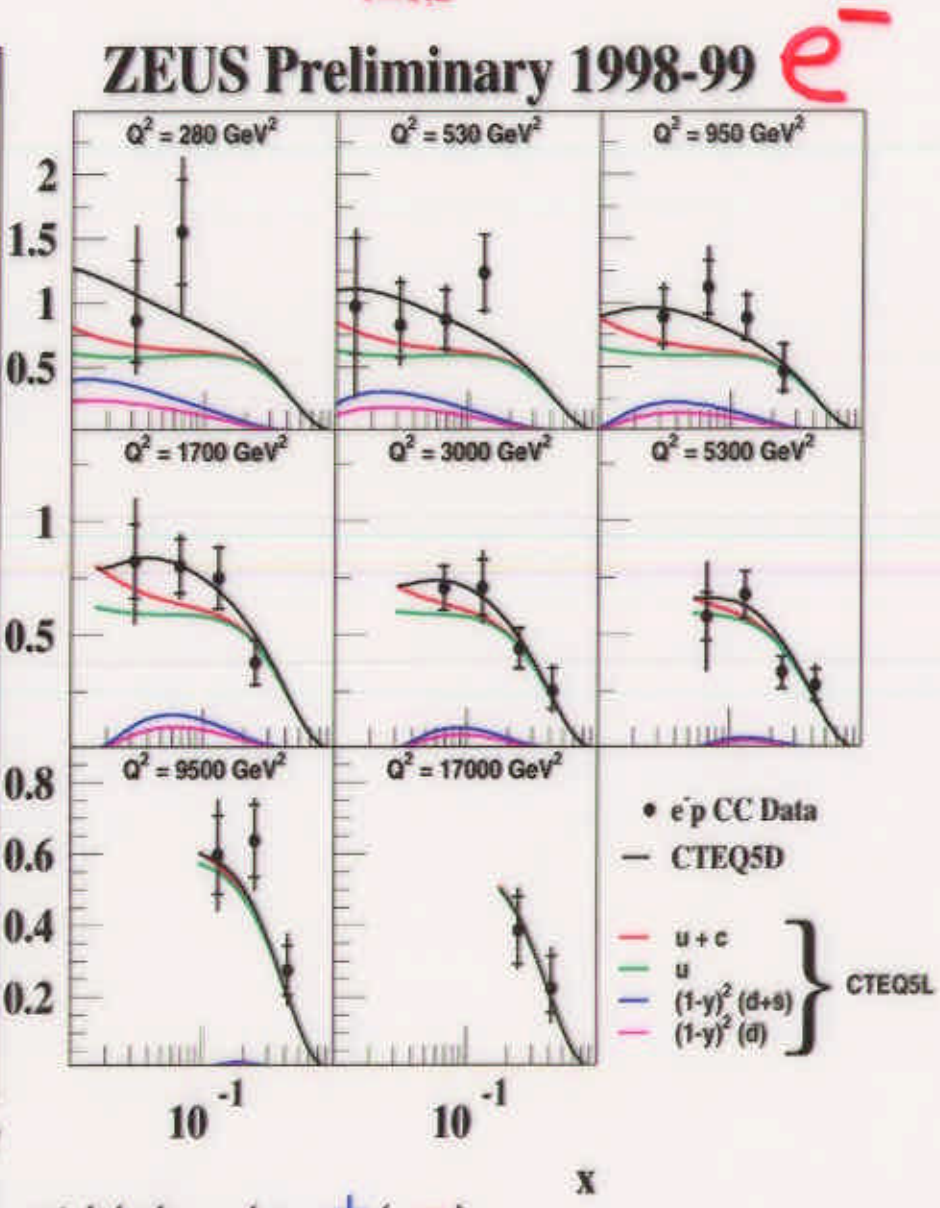
- First measurement of xF_3^{NC} at large Q^2.
- F_L correction is only 10% at lowest Q^2 and lowest x(=highest y).
- Errors are limited by e^- statistics.

Flavor-specific PDF: CC reduced $\tilde{\sigma}_{CC} \equiv \frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{d^2\sigma}{dxdQ^2}$

e^+ $\tilde{\sigma}_{CC} = x\sum_{i=1,2}[\overline{u_i} + (1-y)^2 d_i]$

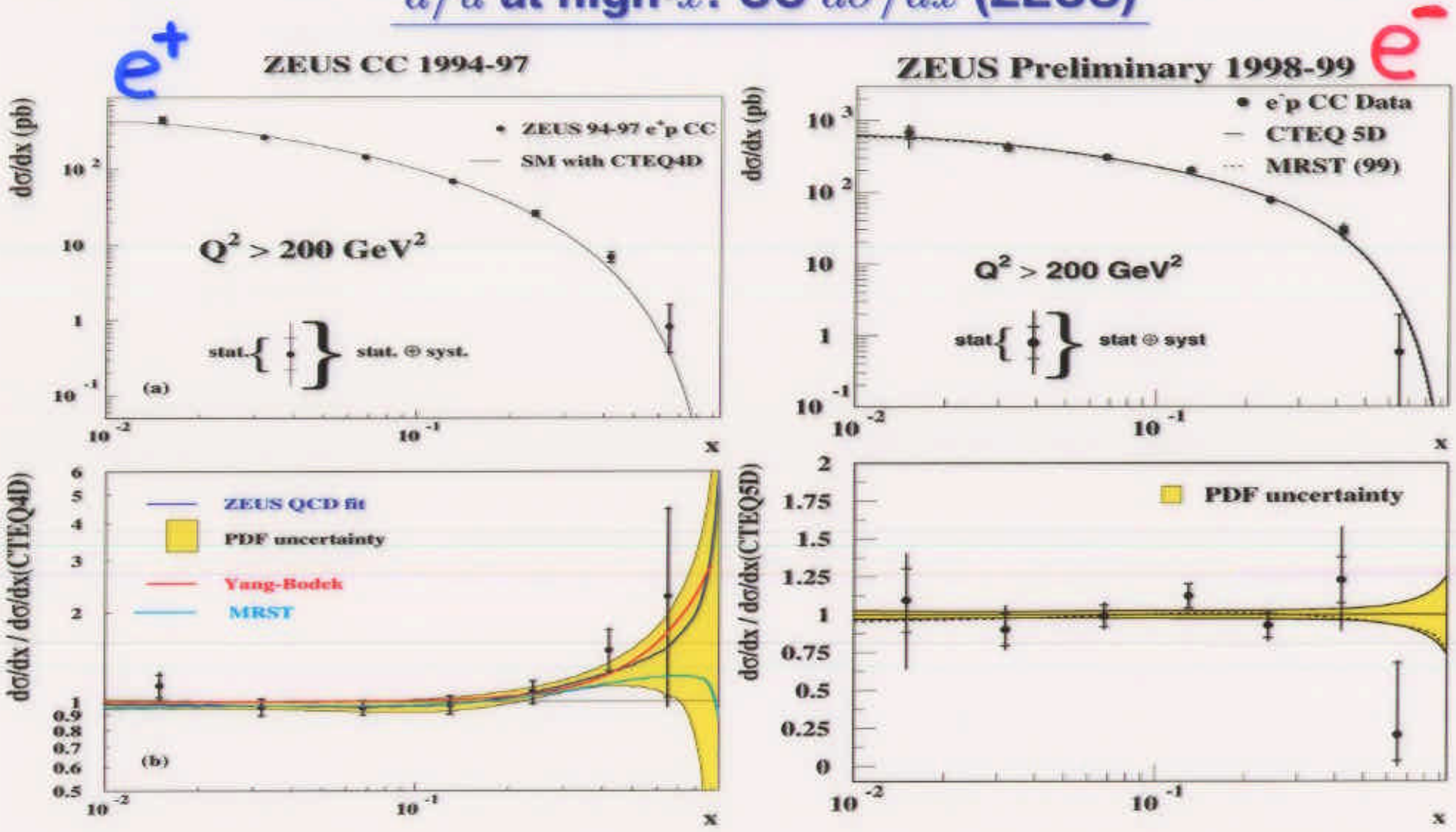
$\tilde{\sigma}_{CC} = x\sum_{i=1,2}[u_i + (1-y)^2 \overline{d_i}]$ e^-





- Sensitivity to d-quark (u-quark) density at high-x in $e^+(e^-)$.

d/u at high-x: CC $d\sigma/dx$ (ZEUS)



- Large uncertainty at high-x where d-quark dominantly contributes.
- Yang-Bodek (= a reanalysis of NMC $F_2{}^d$) $\Rightarrow$ increase d-quark.($d/u \to 0.2$ at $x \to 1$).

- $e^- p$ CC is sensitive to u-quark density at high-x.

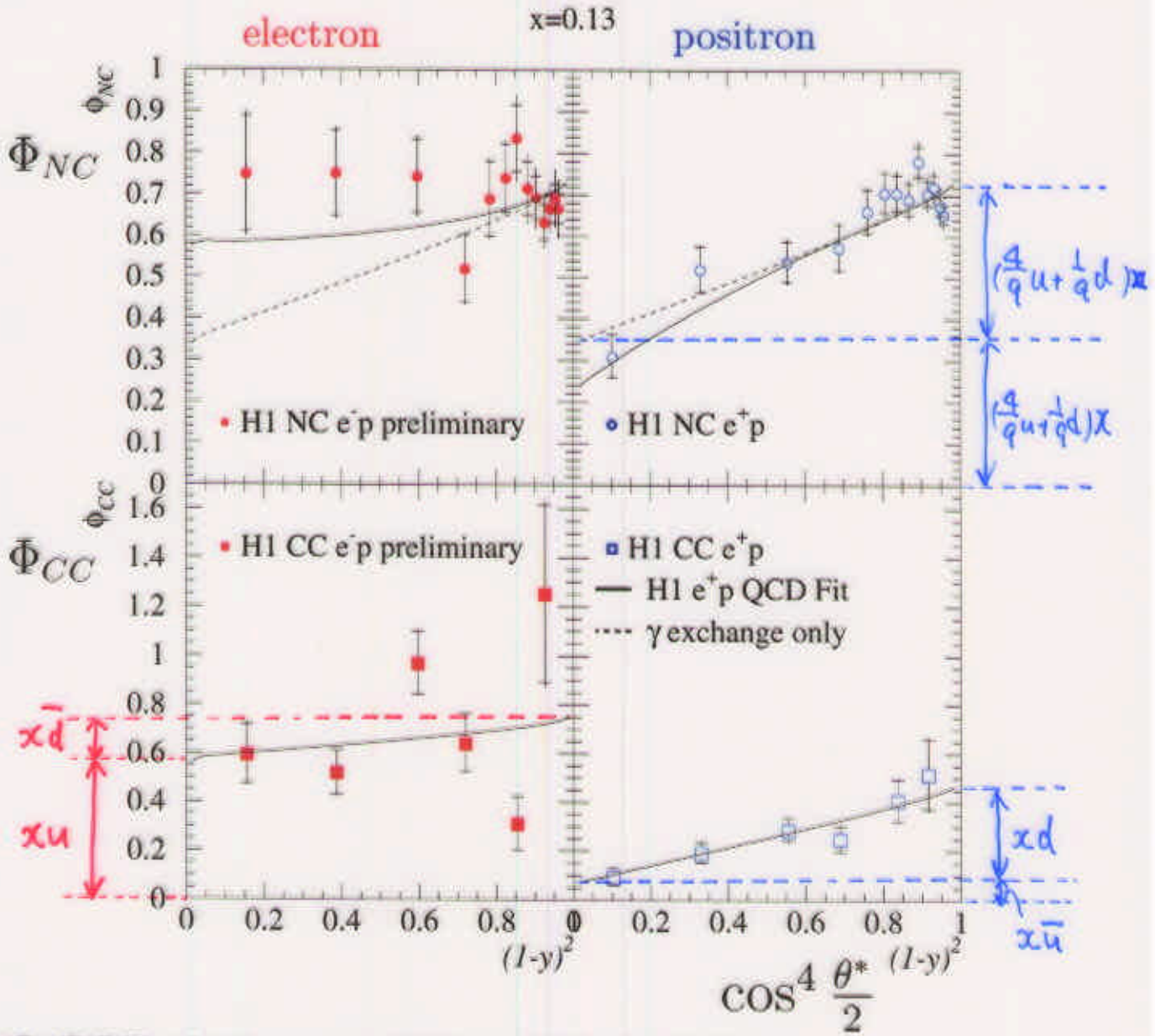
- HERA now provides d/u at high-x at high-Q^2 (=free from target-mass and higher-twist effects etc.) and suggests a higher d/u.

An intuitive PDF visualization: $\tilde{\sigma}$ vs $(1-y)^2$

$$\Phi_{NC} \equiv Y_+ \tilde{\sigma}_{NC} = (F_2^{NC} \mp xF_3^{NC}) + (1-y)^2 (F_2^{NC} \pm xF_3^{NC})$$
$$= x\left(\tfrac{4}{9}u + \tfrac{1}{9}d\right)\{1 + (1-y)^2\} \quad \text{for } \gamma\text{–only, LO.}$$

$$\Phi_{CC} \equiv \tilde{\sigma}_{CC} = \begin{cases} x\bar{u} + (1-y)^2 xd & \text{for } e^+p \\ xu + (1-y)^2 x\bar{d} & \text{for } e^-p \end{cases}$$

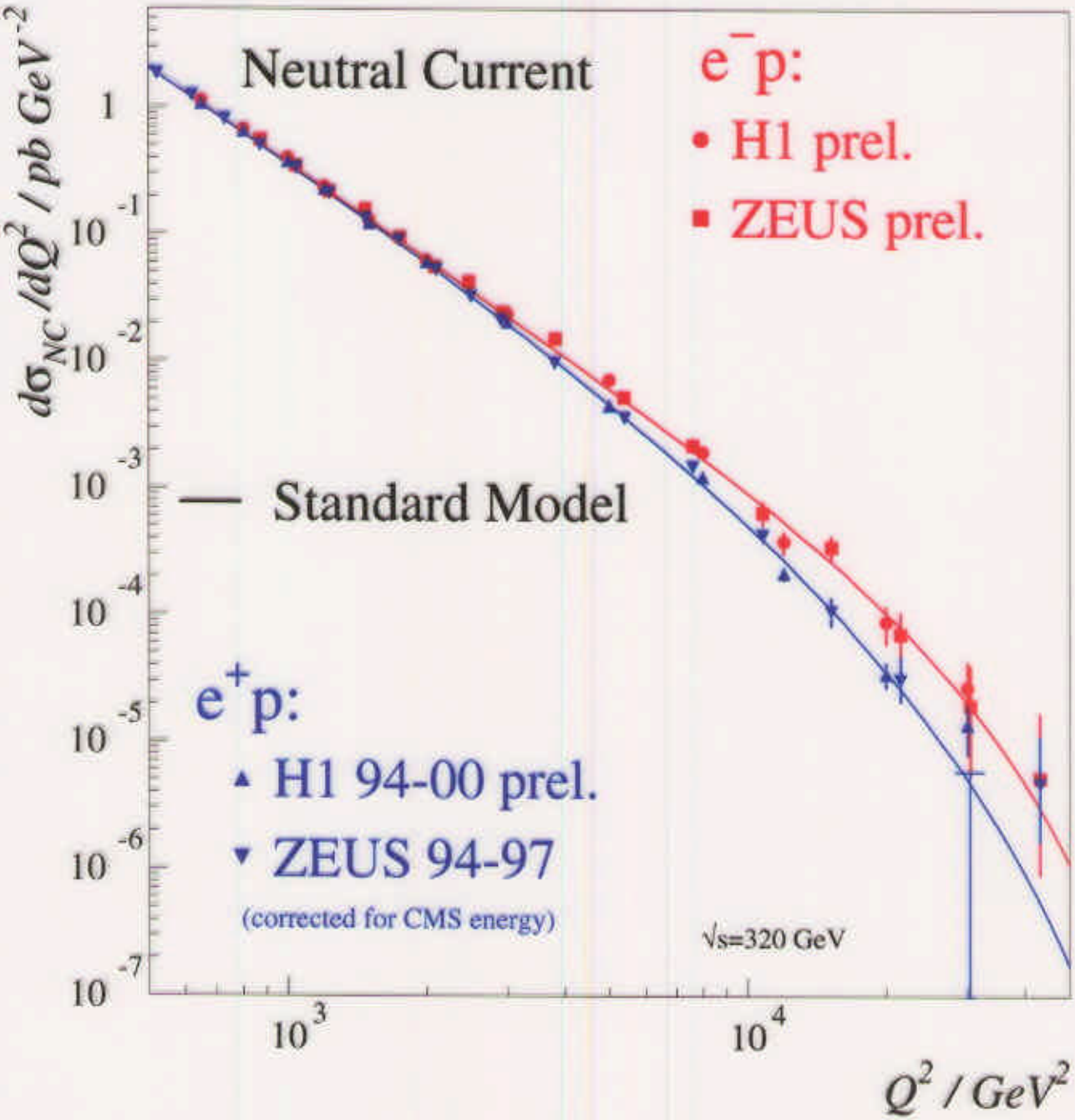
At $x \approx 0.1$, i.e. in an approximate Bjorken scaling region,
$\Rightarrow$ helicity structure can be seen separately: $(1-y)^2 = \cos^4\theta^*/2$:



- NLO-QCD gives a good description of data.
- Naive QPM gives an intuitive picture of PDF and agrees within $\sim 20\%$ level.

NC $d\sigma/dQ^2$: investigate to the smallest λ

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \times \{Y_+ F_2^{NC} \mp Y_- x F_3^{NC} - y^2 F_L^{NC}\}$$

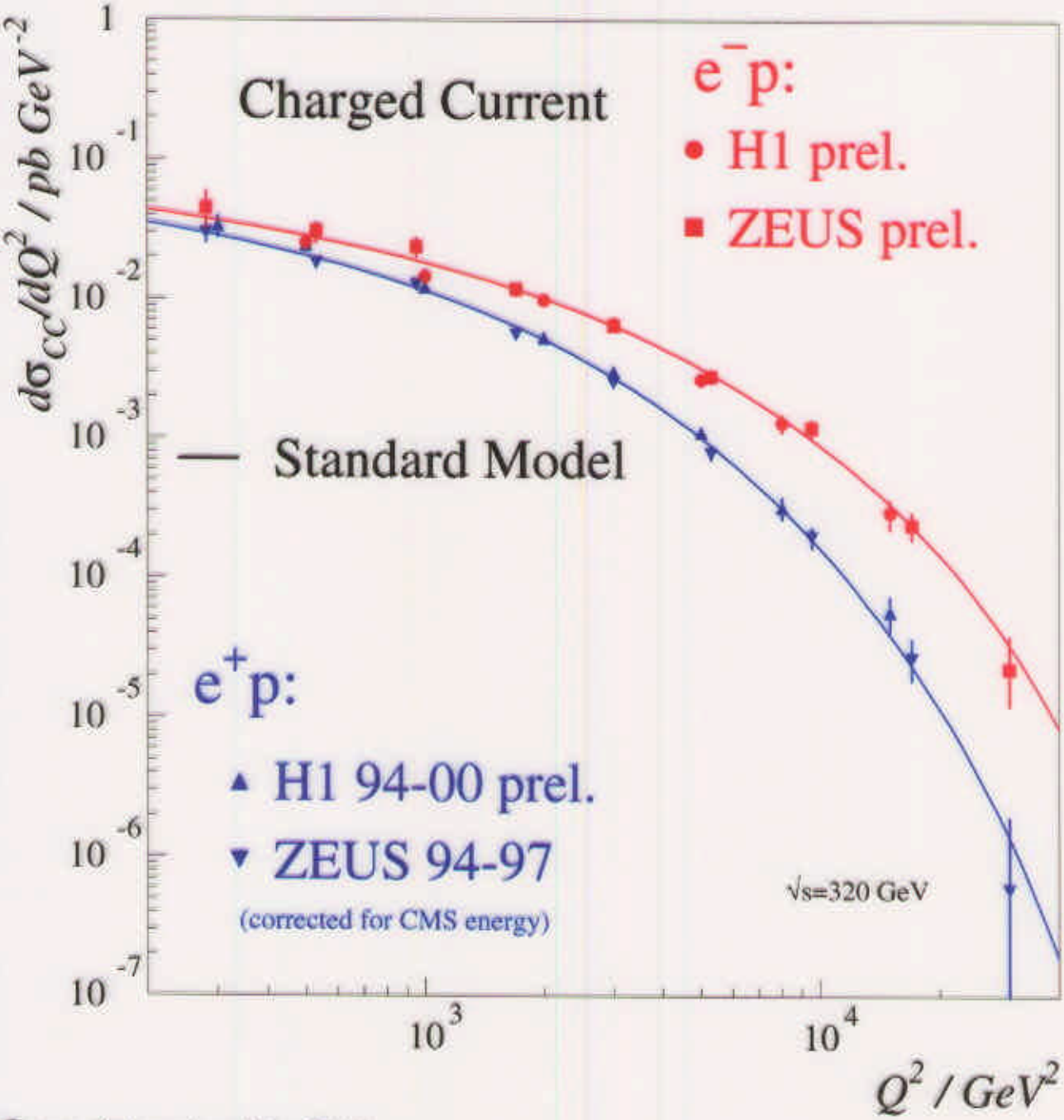


- Measured cross sections agree well with SM predictions 6 orders of magnitude.
- NLO-QCD describes data up to the very high Q^2: $Q^2 \lesssim 20000$ GeV^2!

CC $d\sigma/dQ^2$: investigate to the smallest λ

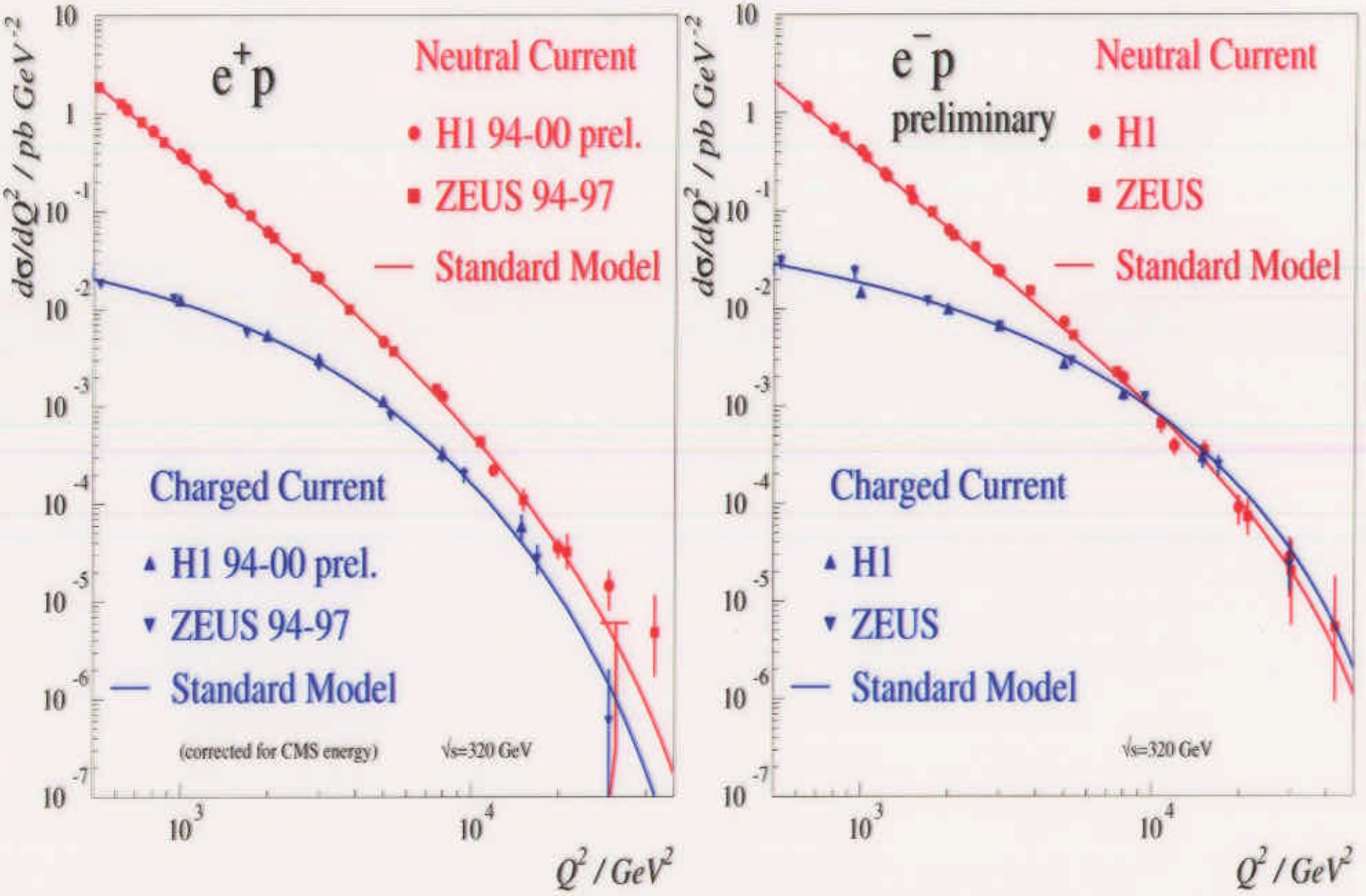
$$e^+p: \frac{d^2\sigma}{dxdQ^2} = \frac{G_F{}^2}{2\pi}\left(\frac{M_W{}^2}{M_W{}^2+Q^2}\right)^2 \times \sum_{i=1,2}[\overline{u_i} + (1-y)^2 d_i]$$

$$e^-p: \frac{d^2\sigma}{dxdQ^2} = \frac{G_F{}^2}{2\pi}\left(\frac{M_W{}^2}{M_W{}^2+Q^2}\right)^2 \times \sum_{i=1,2}[u_i + (1-y)^2 \overline{d_i}]$$



- Consistent with SM.
- e^-p data order of magnitude above e^+p due to:
  $\sigma(e^-p) \propto (u+c)$ while $\sigma(e^+p) \propto (1-y)^2(d+s)$.

High-Q^2 DIS at HERA: Electro-weak Unification



EW sector in CC: M_W determination

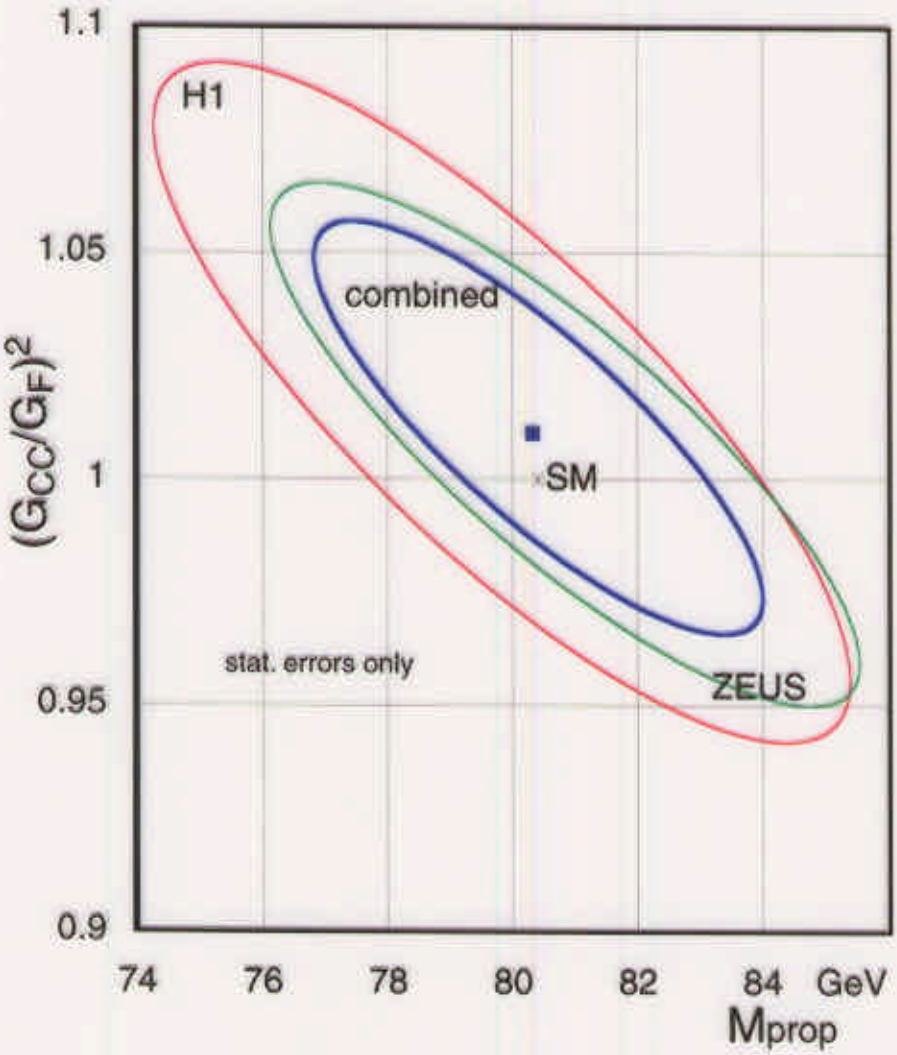
$$d\sigma/dQ^2 \propto {G_F}^2 \times (\frac{M_W^2}{M_W^2+Q^2})^2,$$

(PDG'98: $M_W = 80.41 \pm 0.10$ GeV).

- Unconstrained fit

⇒ spacelike measurement of M_W.

⇒ complementary to timelike measurements at LEP/Tevatron.



- G_F-fixed fit : Fitting the shape.

⇒ measurement of the propagator mass.

$M_W = 81.4^{+2.7}_{-2.6}(\text{stat.}) \pm 2.0(\text{syst.})^{+3.3}_{-3.0}(\text{PDF})$ GeV (ZEUS)

$M_W = 80.9 \pm 3.3(\text{stat.}) \pm 1.7(\text{syst.}) \pm 3.7(\text{theo.})$ GeV (H1)

Summary

We have now all 4 cross-sections; NC, CC for e^+, e^-, precisely measured at HERA!

NC double differential cross-sections: test of pQCD.

- First extraction of xF_3^{NC} at large Q^2.

CC double differential cross-sections: flavor-specific PDF.

- Sensitivity to d/u-ratio at high-x.

$d\sigma/dQ^2$: to the very high Q^2.

- $Q^2 \lesssim 20000$ GeV^2: pQCD OK!
- EW-unification observed.

EW sector in DIS.

- M_W determination.

Outlook

→ Sep. 2000 : End of HERA 1st era.
2001 → : HERA upgrade, high luminosity + e-polarization

- Luminosity: 100 pb^{-1} ('92–'00) ⇒ 1000 pb^{-1} ('01–'06).
- e-polarization: 70% prospected.

⇒ High precision SF measurement at medium∼high Q^2, e.g determination of d/u-ratio etc...
⇒ EW physics, e.g. determination of u,d-quark couplings to Z^0 etc...

Summary: ALL 4 NOW.